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Final Report (End of Project)

Terrestrial Plasmasphere Feature Tracking and Volume Visualization via Tomographic Backprojection

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1 Introduction

In this report, we summarize the efforts on and outcomes of the work on AISRP project NAG5-12109. The project focused on recovery of terrestrial plasmasphere features (principally, the equatorial plasmasphere's plasmapause and the volumetric distribution of the plasmaspheric plasma) using a short sequence of NASA IMAGE EUV images of the terrestrial plasmasphere. The project began in mid-April 2002 and completed in fall 2006.

1.1 Summary of Accomplishments

In the project, techniques that enable exploitation of the EUV data were developed. In addition, some existing techniques were analyzed. The developed techniques were built into a web tool that is freely available to the scientific community. The techniques allow the creation of derived data products that are suitable for scientific study. Work completed in the project allows the volumetric visualization of plasma distributions in the plasmasphere by traditional volume rendering methods and the manual observation of plasma features, including observation of features over time. Methods to track plasma features were also explored.

1.2 Original Aims

The project had three main aims. One of the aims was to develop tomographic backprojection techniques that allow reconstruction of the plasmsphere's plasma distribution from a time-series of the EUV images. A major effort toward this aim was to develop a method that allows recovery of the equatorial-plane plasma distribution. A secondary goal was to allow recovery of the plasma distribution throughout the plasmasphere. The second aim of the project was to develop techniques that support tracking of plasmaspheric features in a time-series of EUV data. The third aim of the project was to provide a community-accessible interface to tools that implement our techniques.

1.3 Problem Background

Reconstructing the volumetric distribution of plasma from EUV images is a challenging problem because only a limited number of views of the plasmasphere can be used in a reconstruction. In particular, since only one EUV image is collected each 10 minutes and the plasmasphere is changing over time, it is not practical to use many (image) views as the basis for the reconstruction. Our approach to solving the reconstruction problem is via use of algebraic tomographic reconstruction techniques that use as few IMAGE EUV images as possible.

In the algebraic methods, the volume of space for which a distribution needs to be recovered is modeled as a set of cells or points. When applied to EUV data, this involves viewing each pixel in an EUV image as containing the integration of the energy emissions at cells or points along its line of sight. The integrations can be expressed as a system of equations. If there are enough measures involving each location whose emissions are to be recovered, the solution of the system (by linear algebraic methods) will produce the emissions at each location of 3-space. In the EUV data, the emissions measured at each location correspond directly to plasma particle concentrations, so solution of the reconstruction using an algebraic method yields the plasma distribution throughout 3-space. Algebraic methods for tomographic reconstruction problems have commonly been used when the number of views is limited, as is the case in our problem.

The system of equations for an algebraic reconstruction is typically very large. Its size depends on both the resolution of each image and on the number of images in the sequence. Although the systems can be quite large (in our work, systems as large as 100,000 by 5,000 have been considered), the systems tend to be sparse. Sparsity can be exploited to reduce computational demands as well as to increase stability and/or accuracy of solution. In this project, we have exploited the sparse nature of the matrices. We have also explored how physical constraints and a physical distribution model can be exploited to enable accuracy in recovery.

2 Brief Progress Summary

In this section, the progress on the project is briefly summarized. A brief background is given to help orient the reader, but to make this report a tractable length and to avoid what could be unnecessary duplication, many low-level details have been omitted.

2.1 Year One Overview

In the first year of the project, we considered use of tomographic reconstruction to recover the plasma density distribution throughout the plasmasphere using a small time-sequence of IMAGE EUV images. Some of the items considered were the impacts on reconstruction accuracy of (1) the number of views in the sequence, (2) noise, and (3) the sampling model. We also began exploring the impact of exploiting physical constraints in the tomographic reconstruction of the plasma density distribution.

One of the main considerations during Year One was if a point-sampling or volume-sampling model was best. It is typical in tomographic reconstruction to use a point-sampling model, which means that the reconstruction problem is viewed as the problem of finding the instantanious distribution at isolated points in 3-space. An alternative for plasma distribution reconstruction is to use a volume-sampling model in which the reconstruction problem is viewed as one of determining the plasma distribution within subvolumes of the plasmaspheric envelope of the Earth. In volume-sampling, the 3-space in which the reconstruction is desired is considered to be tiled by cells that do no overlap but which do fill the entire space. The reconstruction must then determine the plasma distribution within each cell. Point-sampling can be performed with somewhat less computation than volume-sampling. Our research in Year One culminated in the finding that a volume-sampling approach to reconstruction could be more accurate than the conventional point-sampling approach, especially in the presence of noise [16]. We also found that volume-sampling does not require a substantial amount of additional computation over point-sampling since the sampling process is only a small component of the total computation time.

During Year One, we also began exploring the impact of the matrix solution mechanism on plasma distribution reconstruction. Most existing algebraic techniques for tomographic reconstruction have used iterative mechanisms. Typically, those mechanisms refine the density estimate for one cell per iteration and terminate once some measure of error appears to have reached a minimum. Such mechanisms can descend to locally optimal but globally non-optimal solutions. We considered such mechanisms versus direct solution mechanisms. The direct mechanisms seek a global solution to the reconstruction problem. Historically, such approaches were avoided because of their memory requirements, which exceeded the capabilities of most computers when the algebraic reconstruction algorithms were first developed more than 2 decades ago. Increasing computer memory capacity over the years has made many problems potentially solveable using direct mechanisms, although there have been few reports of use of such mechanisms. We found that, for plasmasphere density reconstruction, a direct solution mechanism can offer accuracy that is on par with the accuracy of the iterative mechanisms [16], in addition to having less risk of producing a result that is globally very poor.

2.2 Year Two Overview

In Year Two, our work primarily involved two foci: exploiting physical constraints to allow accurate reconstruction from a limited number of views and tracking plasmaspheric features using the active contours (snakes [4]).

2.2.1 Exploiting Physical Constraints

The first major undertaking in Year Two was exploration of the effects of exploiting physical constraints on reconstruction accuracy. Specifically, we initially investigated the impact of north-to-south symmetry exploitation. We also investigated exploiting an empirical model of plasmaspheric plasma distribution developed by Huang et al. [1] from an IMAGE RPI-based study.

The plasmasphere's plasma density is approximately symmetric about the equator, although at times other than the equinox, the density in one hemisphere about the geomagnetic equatorial plane can be as much as 10% higher than the density in the other hemisphere [1]. For time periods in which the plasma density is nearly symmetric about the equator, the plasma reconstruction process can be aided by exploitation of this physical constraint. In Year Two, we incorporated the capability to exploit such a constraint in our tomographic reconstruction methodology. For such times, the reconstruction need only solve for the distribution on one side of the equator; the cells on the other side of the equator have a symmetric distribution and need not be solved for explicitly. The equatorial symmetry constraint serves to thus approximately halve the number of unknowns via approximately doubling the number of samples. We have found that such an approach can improve the accuracy of reconstruction [10] by about 10% over standard reconstruction without exploiting physical constraints. We also began planning a web-accessible interface to our method to enable space science community use.

Huang et al.'s [1] study of plasmaspheric densities found that the density distribution along a field line can be reasonably well-modeled as a function of magnetic latitude and radial geocentric distance. In Year Two, we began to investigate how to exploit the model in volume reconstruction. It essentially describes the plasma density at any location on a given field line as latitudinally varying. Exploitation of the model allowed us to further reduce the number of unknowns in the tomographic reconstruction. Essentially,

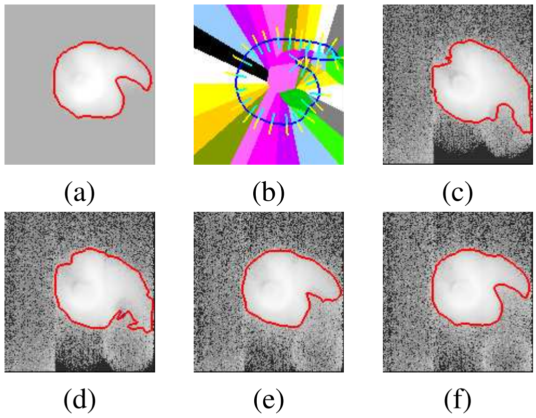


Figure 1: (a) Snake after constrained evolution. (b) Voronoi diagram for a snake. (c – f) Snake on a time-series sequence of EUV images, (c) 20^{th} frame, (d) 25^{th} frame, (e) 30^{th} frame, (f) 35^{th} frame.

exploitation of the model allows solution for only the equatorial plane's cells; the plasma densities in other cells can be determined by application of the latitudinal variation model. Incorporation of the latitudinal variation model into our reconstruction framework proved to be a little tricky, but eventually the model was incorporated. The impact on reconstruction accuracy from exploiting the Huang et al. model was also benchmarked. To establish a reliable baseline, the benchmark was performed for a known (i.e., synthetic) scenario. Incorporation of Huang et al.'s model was found to improve reconstruction accuracy about three-fold over standard reconstruction without exploiting physical constraints.

2.2.2 Feature Tracking

The second major undertaking in Year Two was development of a new snake-based method to track the boundary of the plasmasphere in a time-series of EUV images. The method can potentially allow study of change in the plasmapause, including the evolution of plasmapause boundary features over time. This method is described in a paper that appeared at the 2004 International Conference on Pattern Recognition (ICPR) [2]. The snake-based method uses a template of a representative EUV image to position the snake near the center of an EUV image. Then, the snake is inflated. The inflation process uses image features, especially high gradient points, to attract the snake toward the plasmapause, which is typically characterized by a sudden decrease in plasma density. The attraction process also uses a Voronoi diagram to prevent the snake inflation process from creating loops (i.e., self-intersections in the boundary). The new snake-based plasmapause tracking method exhibits good accuracy—on the order of 1 pixel average error from a manually-traced plasmapause boundary.

Figure 1, which is taken from the ICPR paper [2], demonstrates the performance of our snake-based plasmapause tracking for one image sequence.

2.3 Year Three Achievements

In the third year of the project, we (1) further studied the plasmapause boundary and boundary feature localization problems, primarily by considering refinements of the snake-based feature tracking scheme, (2) investigated methods for determining the global and the local rates of co-rotation of the plasmapause, (3) developed a new method for mapping the boundary of the plasmapause in an image to the Earth's geomagnetic equatorial plane, and (4) constructed an alternate way to utilize the Huang et al. empirical model of the plasmasphere that appears to allow quite accurate plasmaspheric volume reconstructions. An overview of these achievements follows.

2.3.1 Plasmapause Feature Localization

The snake-based approach for tracking the plasmapause was further tested and refined during Year Three, leading to publication of a report on its performance [3]. The efforts involved experimenting with the parameters that govern the attraction process described in Section 2.2.2 and determining the impact of noise and artifacts on accuracy. It was found that in some cases, high levels of noise or image artifacts presented challenges for the automated method. Currently, methods that can succeed for these cases are under study. One advantage of plasmapause feature tracking is that it can give scientists studying the evolution of features a technique to objectively and automatically localize the features across a large set of data. Several approaches that could serve as substitutes for snake-based plasmapause detection were also considered in Year Three, based on feedback received at the conference where our snake method was introduced. The alternatives were found to be less suitable to our problem than were the snakes.

One of our interests has been to be able to track features of interest, particularly features on the plasmapause, such as notches, the tail of the plasma plume, etc., over time. Although the snake-based approach is often successful in automatically localizing the plasmapause as a whole, the approach is less useful for detecting features of interest, especially when the need is to correlate feature positions in different images. During Year Three, we explored several methods for detecting and tracking features. We had some success in the methods developed for finding the tip of the plume tailing out from the main body of plasma in the terrestrial plasmasphere and for finding the "pit" between the plume and the main body of plasma using a variation on the $\theta - s$ curve-matching approach of Perkins [7]. Those methods need more refinement, however, and will have to be finished in future efforts.

2.3.2 Co-Rotation Rate

The $\theta - s$ curve-matching approach discussed above for feature tracking can also be used to determine the rotational shift between two similar curves. During Year Three, we implemented and tested such an approach, focusing first on raw EUV images but later on the equatorial-plane plasmapause boundary, which was determined using the method that will be described in Section 2.3.3. Access to such an approach could benefit studies of plasmapause temporal evolution and hence directly benefit the plasma sciences community, however our primary interest in exploring such an approach was to aid our tomographic reconstruction method. Since the plasmasphere rotates over time, knowledge of the rotational amount could be used to correct the reconstruction for the rotation. For example, if the contents of a cell at position P_0 at time t_0 rotated to a new position P_1 by time t_1, the reconstruction should consider the contents transformed to the position P_1 at time t_1 to be the same as the contents that were at position P_0 at time t_0. Past empirical studies have suggested that the plasmasphere co-rotates with the Earth at a rate that is about 85 to 90% of the Earth's rotation rate. It is a bit difficult to reliably determine the rate of co-rotation using the $\theta - s$ approach, however, as discussed in one of the works resulting from the project [5].

2.3.3 Plasmapause Boundary in Equatorial Plane

One of the primary significant results for Year Three was the development and presentation of an algorithm that can more correctly project the plasmapause boundary from an EUV image to the equatorial plane.

Previously, Roelof et al. [8] have presented the Edge Algorithm for projection of the plasmapause boundary from an EUV image to the equatorial plane. The Edge Algorithm presumes that the plasmapause has a convex shape, and, for a convex-shaped plasmapause, the Edge Algorithm is provably optimal. For each pixel that appears to be a point of high intensity gradient, the Edge Algorithm considers that that pixel is a line of sight which "glances" the plasmapause. For each line of sight, there is thus a set of values (L, ϕ) representing the combinations of L's and MLT's that are intersected by the line of sight, where the L values are determined using a dipole field model. Each set of values forms a curve in L and ϕ. Thus, the set of all values is a set of curves. By mapping all of the sets of values (L, ϕ) into a planar graph with axes L and ϕ and then considering the "envelope" of space in this plane bounded by the set of curves, a conservative estimate of the magnetic field can be obtained. In fact, each (L, ϕ) curve is the mapping of all the (L, ϕ) combinations encountered along each line of sight, so the interior of the set of curves should be completely inside the plasmapause.

The Edge Algorithm produces the boundary of the plasmapause in the equatorial plane given any input EUV image. The Edge Algorithm is too conservative, however, especially for plasmapause boundaries which are not convex. In such cases, any outward "bump" in the plasmapause boundary will not be present in the equatorial plane boundary. In addition, there are images for which the Edge Algorithm cannot be applied at all because there is no envelope of the set of values (L, ϕ).

By reconsidering the algorithm, it is possible to do better but still produce a cautious estimate of the plasmapause boundary in the equatorial plane. Our reconsideration is what we call the Minimum L Algorithm. In our Minimum L Algorithm, for each line of sight, we find the (L, ϕ) combination for which L is minimum, and we take that as the sole mapping of that line of sight onto the equatorial plane. In so doing, local protrusions of the plasmapause are preserved. We find the boundary of the plasmapause in the equatorial plane by fitting a piecewise B-spline curve to the set of projected (L, ϕ) points.

In fact, while we have studied this algorithm and are the first to describe its steps, it appears that others in the community have used a variation on the Minimum L Algorithm, perhaps due to misunderstanding the original Edge Algorithm.

A comparative illustration of the results of applying the Edge and Minimum L Algorithms is shown in Figure 2. The upper left part of the figure shows the outline of the plasmapause that was manually extracted from the EUV image taken at 11:40 on Day 161 of Year 2001. Below it are the equatorial plane plasmapause boundaries that result from use of the Minimum L and Edge Algorithms. To the right of the image are renderings of silhouettes of the set of dipole field lines that pass through the equatorial plane plasmapause boundaries. The silhouette produced by the Minimum L Algorithm is clearly more similar to the image's plasmapause. In the bottom right of the figure, a comparison of three regions of the equatorial plane boundaries is shown for the two algorithms. In those sub-figures, the Edge Algorithm results are shown in red and the Minimum L Algorithm results are shown in black. In particular, the plume was recovered by the Minimum L but not the Edge Algorithm.

2.3.4 Exploiting the Huang et al. Model

The final task undertaken in Year Three was development of two techniques to exploit the Huang et al. [1] model. The Huang et al. model is based on empirical observation of the plasma distribution using IMAGE RPI data. The observations suggest that plasma density varies latitudinally along each field line as follows:

$$N(L, \lambda) = N_0(L)(1 + \gamma \frac{\lambda}{\lambda_{inv}}) sec^{\beta(L)}(\frac{\pi}{2} \frac{\alpha\lambda}{\lambda_{inv}}), \tag{1}$$

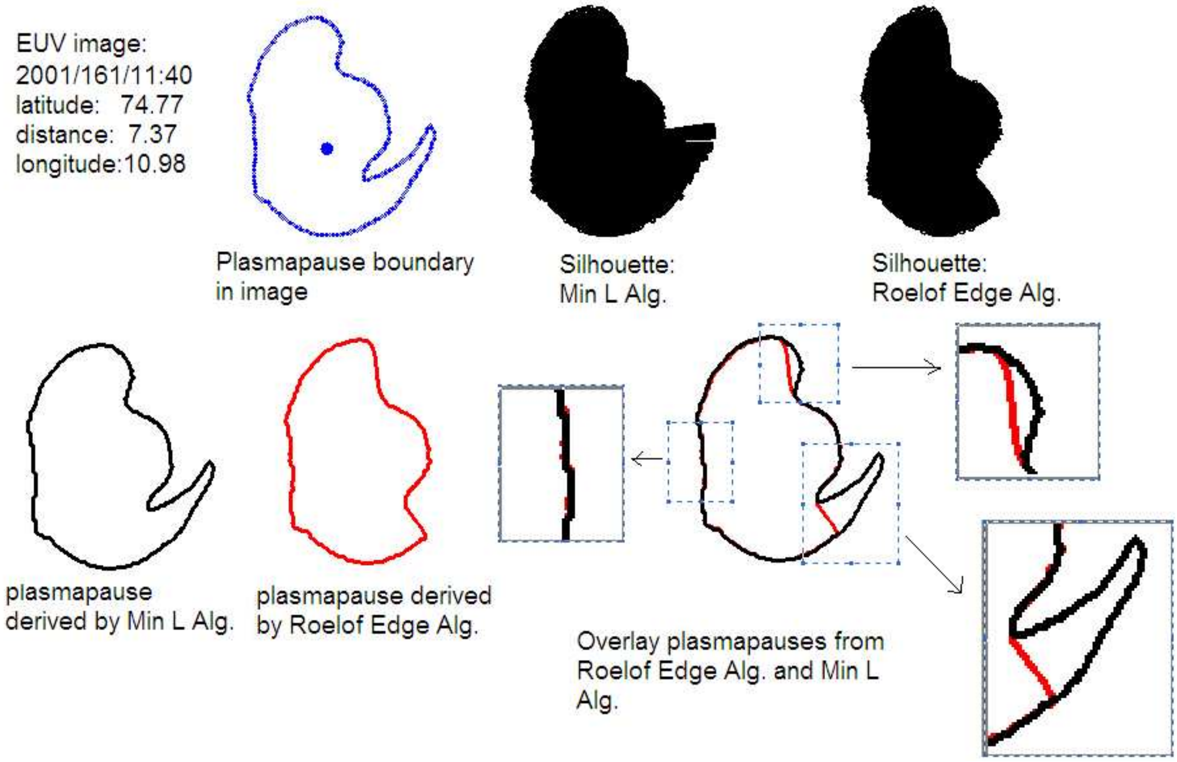
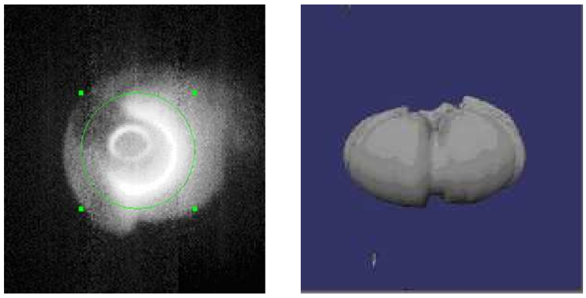


Figure 2: Comparison of Minimum (Min) L and Edge Algorithms



(a) (b)

Figure 3: EUV Image and 3D Boundary of Plasmasphere Reconstruction. (a) Original Image (green outline shows central masked-out area) (b) 3D Rendering of Boundary

$$N_0(L) = A(\frac{B}{L} - 1), \tag{2}$$

$$\beta(L) = R + DL, \tag{3}$$

where $N_0(L)$ is the plasma density at a particular L value in the equatorial plane, λ_{inv} is the invariant latitude in a *L-shell*, γ is a measure of the north-south asymmetry, and the parameters $A = 4833cm^{-3}$, $B = 3.64$, $R = 0.2$, $D = 0.03$, $\gamma = -0.14$, and $\alpha = 1.25$ were obtained by a multi-variant best fit on the measurement s from RPI.

The first of these efforts began at the end of Year Two and involved recovery of the plasma distribution by considering each latitude for a given MLT to have a density value that varied from the value in the equatorial plane according to the Huang et al. model. The second effort took a slightly different approach, and appears to produce quite good results. In the second effort, we used the nonlinear least squares to solve for the unknown parameters in the Huang et al. model for each field line. Specifically, we take the integration expressions for each line of sight and use the nonlinear least squares to solve for the Huang et al. model unknowns across the set of expressions. In Figure 3 an EUV image and 3D rendering of a reconstruction of the plasmasphere are shown. The EUV image is from 07:22 on Day 145 of Year 2000. It is shown in Figure 3(a). The Figure 3(b) is the rendering of the plasma distribution for this time point based on tomographic reconstruction that exploits the Huang et al. model. This rendering is essentially the 3D boundary of the plasmasphere. This rendering was generated by application of our techniques. We believe that this is the first 3D visualization of the plasmasphere based on real image data for an actual time point.

2.4 Progress in Period After End of Year 3

In the no-cost extension of the project beyond Year 3, we developed the web-based tool that allowed easy community use of our most successful techniques. The tool allows for equatorial plane plasmapause determination given a single EUV image and for reconstruction of the plasmasphere's volumetric plasma distribution. The plasmapause determination component of the tool provides for both Edge Algorithm and Minimum L Algorithm reconstructions. To our knowledge, our Edge Algorithm implementation is the first actual reduction of the Edge Algorithm to practice. The tool is available at `http://plasma.cs.uah.edu:8080/plasmasphere/page0.jsp`

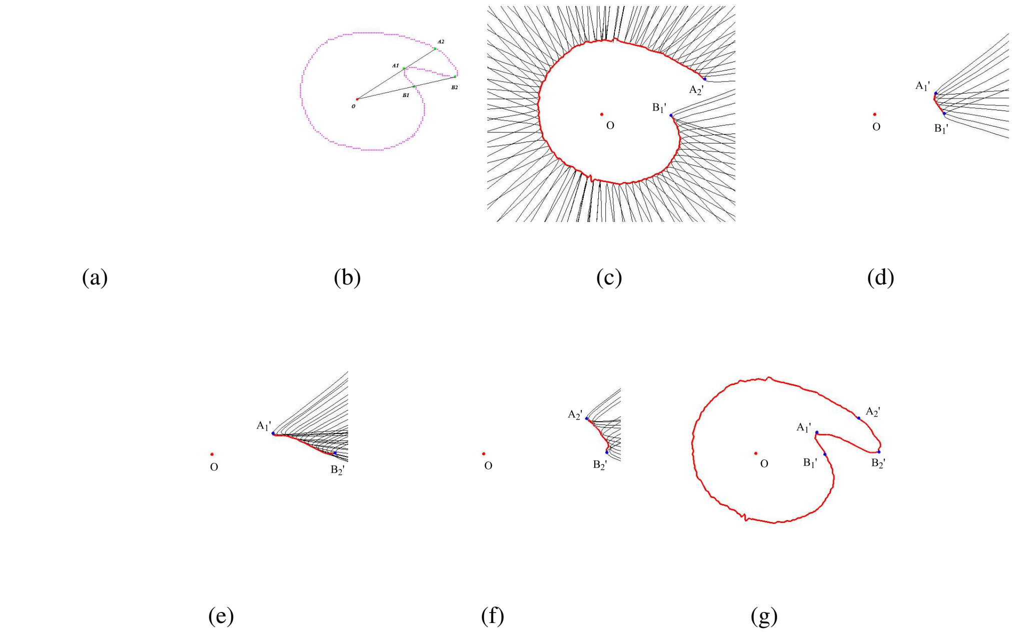


Figure 4: Revised Edge Algorithm Application. (a) 2001/129/10:24 EUV image, displayed after histogram equalization. (b) Labeled plasmasphere silhouette for the EUV image. (c) Envelope for portion of silhouette's (L, ϕ) curves. (d) Envelope for segment B_1-A_1. The curves are shown in black and the envelope is shown in red. (e) Envelope for segment A_1-B_2. (f) Envelope for segment B_2-A_2. (g) Connected envelope segments defining the equatorial plasmapause.

In addition, a revised version of the Edge Algorithm was devised and reported in the literature [13]. The new version is able to operate in some cases where the original Edge Algorithm could not determine an envelope to the set of (L, ϕ) curves, in particular when there is a concavity in the equatorial plane plasmapause. An illustration of the processing steps of the Revised Edge Algorithm is shown in Figure 4.

Finally, an analysis of the Minimum L Algorithm was completed and submitted for publication [14]. (We note that the Figure 4 is taken from that manuscript.) A publication describing our non-linear least-squares approach that exploits the latitude variation model is in preparation.

3 Contributions to Education

Over the course of the project, the education of a number of graduate students has been further by their participation on the effort.

Naveen Santhanam is probably the student who spent the most effort on the project. He worked on the project for Year Two and the first half of the Year Three. His work primarily focused on methods that exploit physical constraints about the plasmasphere to improve reconstruction accuracy. He also worked to address the memory requirements of the reconstruction. Mr. Santhanam was co-author of one published paper ([10]) arising out of the project. His work is well-summarized in his M.S. thesis [9], which was defended in summer 2004.

The student with the second highest level of effort over the project is Ph.D. student Cuilan Wang, who began work on the project in January 2004. She worked on the project throughout the Year Three and the extension after Year Three. Her efforts on the project have involved plasmapause boundary detection [11] and incorporating knowledge of that boundary into the reconstruction scheme to allow further improvement in reconstruction accuracy. She is the party primarily responsible for development of the revision to the Edge Algorithm, which was reported in the literature in Summer 2006 [13]. She also worked with the PI to utilize the Huang et al. [1] physical model of plasma density directly in a reconstruction mechanism. That effort was reported at the 2005 Fall AGU [12]. Finally, she assisted in the effort to build the integrated web-based tool for plasmasphere volume reconstruction [6].

Other students who have been supported over the course of the project include Dr. Huijuan "Jean" Zhang, Raghav Khokale, Simran Brar, Dr. Hongtao Xu, and Ram Kandimalla. Dr. Zhang participated in the early stages of the project. She defended her Ph.D. dissertation near the end of Year Two of the project. Her AISRP-funded research efforts (which validated our volume-sampling approach [16] and established baseline performance expectations for reconstruction performance as the number of views increased) were a significant part of her dissertation ([15]). Ph.D. student Hongtao Xu considered the impact of machine precision on reconstruction during Year Two of the project. M.S. students Raghav Khokale and Simran Brar investigated the reconstruction's sensitivity to noise and number of views and explored how rotational constraints could be exploited. Khokale also worked on determining the rotational rate of the equatorial plasmapause. He wrote a Masters thesis [5] that focused on his work in that area. They worked during Year Three. Ph.D. student Ram Kandimalla worked on down-stream processing issues, primarily related to tracking of plasmapause features over time via a new snake-based [4] mechanism. He is co-author of one peer-reviewed paper ([2]) and one poster ([3]) arising out of the project. Mr. Kandimalla was supported on a part-time basis during some periods of Year Two and Year Three of the project.

We believe that the achievement of educational objectives is one beneficial outcome of this research project. Our research effort is thus both achieving technical objectives as well as improving human capital.

4 End Notes

Although the project officially started in April 2002, we did not really begin research efforts in depth until Summer 2002. Personnel changes near the end of Year Two and during the early months of Year Three put us a little behind where we would have hoped to have been at the end of Year Three. However, the overall project goals were still achieved, thanks to the no-cost extension.

Some of the highlights of the work include the creation of the first methods for reconstructing the plasmaspheric plasma's volumetric distribution, the first reduction of the Edge Algorithm to practice, the creation of an improved variation on the Edge Algorithm, and a web-based platform that allows public access to the tools.

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